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14. ABSTRACT

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Conceptual Design, Feasibility and Payoff Analysis of a Third Stage for EELV

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Improvements in payload performance for the Air Force's EELV are advantageous to mission needs, since payloads typically increase. A third or "kick" stage is one potential solution to provide an incremental improvement in payload mass as well as to provide additional mission flexibility. A classical configuration stage design is very difficult to implement into the EELV architecture due to significant architecture impact. This could translate to vehicle structural changes and or payload volume reduction. Therefore, a stage that has minimal impact on the launch vehicle architecture by accommodating the vehicles's current characteristics is advantageous. A conceptual study addressed these limitations by examining a toroidal shaped stage solution that fits within the current envelope of the respective EELV's payload fairing interface section. This location imposes several kick stage size and shape limitations, but affords minimal changes to the overall existing launch vehicle. The analysis reviewed the overall vehicle architecture, identifying locations for modification or stage shape. Trade studies of various propellant types (LOX/LH2, LOX/RP, LOX/methane, hydrazine monopropellant) were included in the analysis. The effort generated a propellant tank and engine conceptual layout design. The analysis matured the stage design to a sufficient level and quantified the stage's payload payoff for different ΔV missions.

Nomenclature

EELV	=	Evolved expendable launch vehicle
GLOW	=	Gross lift off weight
GTO	=	Geostationary transfer orbit
Isp	=	Specific impulse
LEO	=	Low Earth Orbit
LOX	=	Liquid oxygen
LH_2	=	Liquid hydrogen
POST	=	Program to Optimize Simulated Trajectories
P_c	=	Chamber Pressure
RP	=	Rocket propellant (kerosene)
ULA	=	United launch alliance
USAF	=	United States Air Force
ΔV	=	Change in orbital velocity

I. Introduction

The USAF EELV program currently uses the Atlas V and Delta IV provided by ULA. Both systems currently use a two-stage configuration with the option of multiple solid rocket boosters. A third stage has the potential of increasing delivered payload. As part of feasibly and exploratory activities within AFRL, with the focus of

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increasing the USAF's launch capability, a conceptual design study was performed to explore the potential benefits of a third stage. The inspiration for pursuing this analysis is the classic ΔV vs payload mass shown in Figure 1. From this notional graph, there is a small improvement in payload delivery as the number of stages is increased. Using a target ΔV goal for the payload, the inclusion of a third stage could increase the payload weight percentage (as percent of total vehicle weight) by ~1%. In a large launch vehicle of close to 500 metric tons (~1.1Mlb) that ~1% payload improvement can be quite significant.

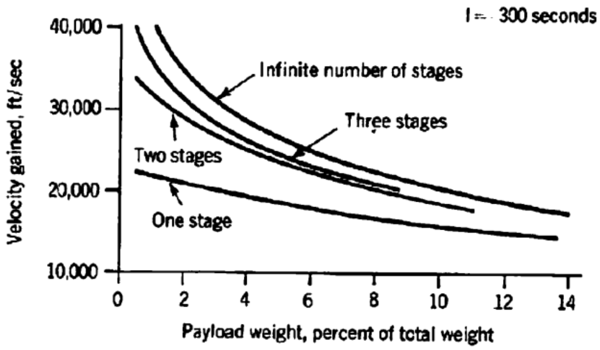

Figure 1. The performance of multi-stage propulsion systems[14]

The study focused on the EELV vehicles since those are the primary DoD launch systems being currently used for large payloads. The study addresses potential payload flexibility and payload improvements, while limited to only publicly available information. The primary figure of merit used in assessing the benefit of a candidate 3rd stage concept payoff is the payload increase at a set ΔV. The primary ΔV values used were for LEO and for GTO.

II. Analysis scope and assumptions

The analysis began with research of the vehicle layouts of the Atlas V and Delta IV. The first resource was the payload user's guide. The analysis identified areas within the vehicle where a third stage will minimally affect the payload volume or stage interfaces. From this study, the location, maximum volume, and stage shape are determined. The allowable volume and shape limits the new stage's maximum propellant mass.

From the third stage volume and shape requirements, the next step was a comparison between different tank shapes. This identified the most volumetrically efficient propellant storage scheme to maximize the amount of propellant carried. The two primary shapes investigated were a grouping of oblate spheroid tanks and a concentric pair of toroidal tanks.

Additionally, because this stage is more volume limited than the 1st and 2nd stages, a potential exists for a pressure fed system to compare well with a typical pump fed propulsion unit. A first order comparison using weight and packaging efficiency identified the most beneficial scheme to use for this concept. For each configuration, a comparison of Pc vs. nozzle area ratio identified the benefit of the higher performance and its tradeoff with weight or mass ratio. With the most promising tank and feed options, a trade analysis using various propellant combinations quantified the total impulse available with each configuration. Propellant combinations ranged from monopropellant (low performance, high bulk density) to bipropellant (high performance, low bulk density), with several intermediate options.

Finally, a basic vehicle performance analysis showed how each propellant combination would affect the payload delivered by an Atlas V. The results allow understanding of the interaction of I_{sp}, mass fraction, propellant bulk density and total impulse on vehicle performance. The propellants analyzed are Hydrazine, N_2O_4/MMH, LOX/RP, H_2O_2/RP, LOX/CH_4, LOX/LH_2 (at MR of 6), and LOX/LH_2 (at MR of 10). The Star 48 motor provided a comparison as a standard 3rd stage implemented in other systems.

A. Vehicle layout and stage envelope analysis

The first step determined a location within the two vehicles that would have the least impact on the overall architecture. The analyses of the vehicle showed a flat torus shaped volume directly above the upper stage and below the payload adapter interface. This location (Figure 2) is currently open space within the vehicle and does not interfere with the payload volume or affect the layout of the vehicle's lower stages. This location is similar for the two vehicles (Atlas V, and Delta IV) with the individual dimensions of the payload adapter and upper stage varying only slightly. Using the Atlas as a baseline, a D1666 payload adaptor provided a conservative design envelope since it is the largest of the standard adaptors.

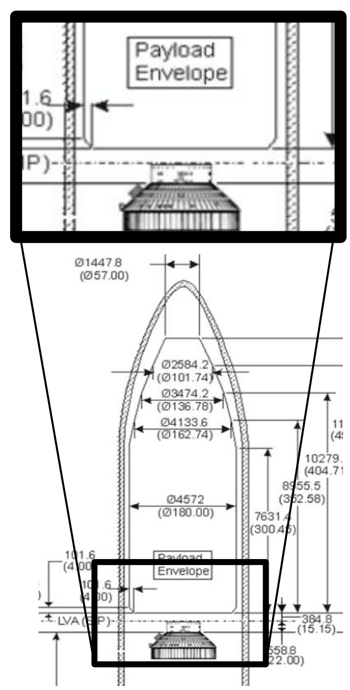

Figure 2. Atlas V payload envelope with attachment ring[1]

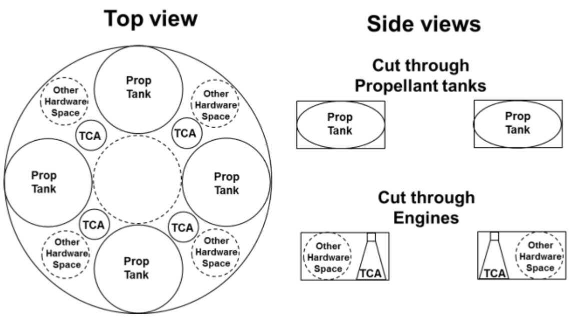

Figure 5. Oblate spheroid tank configuration.

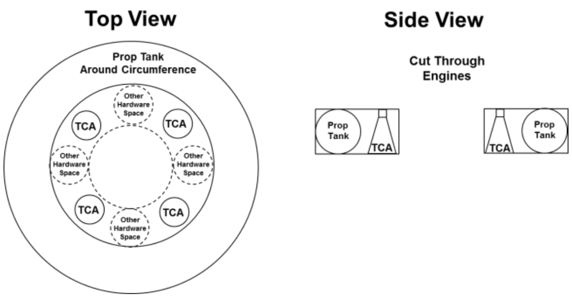

Figure 5. Monopropellant toroid tank configuration

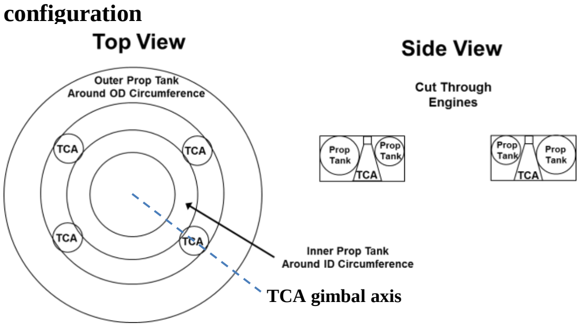

Figure 5. Bipropellant toroid tank configuration

The flat torus is similar to a "thick washer shape." Its dimensions are a height of 0.89m (35in), inner diameter of 1.68m (66in), and an outer diameter of 5m (196in). This is a challenging geometry for a rocket stage Thus the design challenge is filling this envelope as efficiently as possible. The different tank and chamber layouts yield the weight and propellant capacities. Two primary configurations were studied: a multiple spheroid arrangement and a concentric pair of toroidal tanks. It was found that each tank configuration provided different propellant volume capacity within the envelope.

The oblate spheroid configuration (Shown in Figure 3) consisted of four spheroid tanks, each based on a 2:1 ellipse. The maximum minor axis radius of ~0.44m (17in) is due to height limitations within the stage. The oblate spheroid configuration places the TCAs near at the inner diameter (payload ring) and leaves four quadrants of space for other hardware such as conditioning, turbopumps, gas generator (GG), batteries and electronics.

The toroidal tank configuration has two sub-configurations depending on either the monopropellant or the bi-propellant configuration. The monopropellant configuration only has one tank placed abutting with the outer diameter of the volume as shown in 4. The bi-propellant configuration has two concentric toroids with the TCA placed in between as shown in Figure 5. The monopropellant toriodal tank configuration has similar placement of the TCAs near the payload adapter, leaving additional space in-between each TCA for miscellaneous items. The bi-propellant configuration has the two toroidal tanks arranged in a concentric fashion: the inner toroid is next to the adapter ring and the outer one near the payload fairing wall. The TCA's are arranged between the two tanks.

The baseline engine arrangement is a four-bellset. The stage total thrust is 66.72kN (15000lbf). The four chambers, at an individual thrust of 16.68kN (3750lbf), provide the stage total thrust. The four TCAs are arranged to allow for a symmetric thrust along the center axis. Due to the possible lack of access or accommodation inside the payload adapter ring, the designed was constrained to apply all components to the exterior of the ring. Additionally, splitting the propulsion between four TCAs allows for an increase of the area ratio attainable within the engine size constraints. Each TCA gimbals along one axis with the axis extending outwardly from the center of the adapter ring.

B. Comparison of pressure fed vs pump fed system on weight and packaging

Because of the large number of potential configurations (especially with a large spectrum of propellants options), a down selection process was necessary for the tank configurations and the propellant feed systems. As a baseline, the monopropellant hydrazine served to provide that roadmap. Pure hydrazine is not an attractive propellant, but it serves two functions: simplifies the overall configuration trade analysis by using only one propellant and "bookends" the system level analysis by having a propellant that is significantly low performance to further gain insight into the relationship between I_{sp} and bulk density. The list of configurations is:

- Oblate spheroid tanks
  - Pump fed
  - Pressure fed
- Toroidal tank
  - Pump fed
  - Pressure fed

For each configuration option, a P_c vs. area ratio trade describes the benefit of the higher pressure. The maximum length of the chamber is consistently limited to 0.89m (35in) in height. A higher P_c yields a higher area ratio, which delivers a higher I_{sp}. The examined P_c range was from 3.45MPa (500psi) to 10.34MPa (1500psi). A pressure below 3.45MPa (500psi) impacts performance and size and a higher pressure than 10.34MPa (1500psi) does not significantly increase performance and increases complexity and TPA power or pressurization requirements.

The pump fed option uses a GG cycle. Due to the relatively low Pc, a GG system should help to minimize losses in performance when compared to a high performance closed cycle. In addition, for this early trade discussion, a cycle, which is amenable to the most number of propellant combinations, is beneficial. helium is used for turbine spin start and tank NPSH pressurization at 0.172MPa (25psi) and is stored in high pressure bottles. The Turbomachinery fits within the interstices of the propellant tanks and TCAs. For the hydrazine system, the GG uses a catalytic bed for gas generation.

The pressure fed option requires more helium but does not suffer from a performance loss due to GG flow. The helium storage tanks are at very high pressure, up to 83MPa (12Kpsi). A typical pressure budget between the TCA and the propellant tank determines the helium tank pressure and flow rate. However, for some toriodal configurations, the required helium increased to the point where additional helium bottles replaced two TCAs to allow for higher helium capacity. The two larger TCAs have reduced area ratio and, thus, reduced I_{sp} .

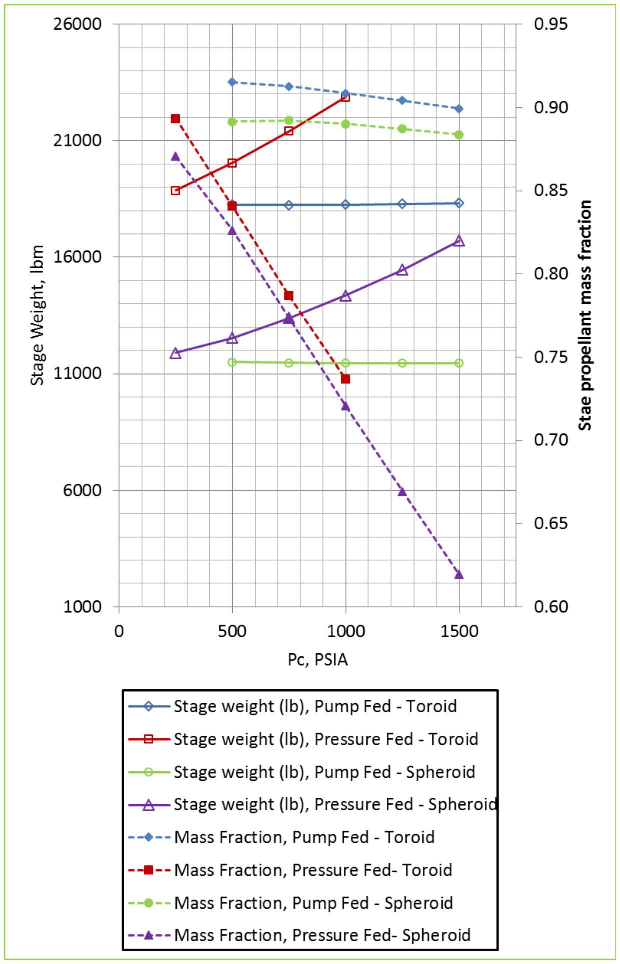

Figure 6. Stage weight and propellant mass fraction for baseline Hydrazine monopropellant 3rd stage depending on chamber pressure

Performance values were computed from standard analytical tools, existing data or engineering judgment to describe performance losses of a thrust chamber of this size and type. An ablative chamber serves as the TCA for both pressure fed and pump fed configurations. A bottoms-up weight schedule for major components provides the initial weight estimate with scaling or first principle calculations for additional miscellaneous components. The intent of the results is to identify significant major comparison *trends* with the understanding that *absolute* values will include significant uncertainty.

Figure 6 demonstrates the higher propellant mass fraction of the toroidal concept for both the pressure fed and the pump fed options. This higher propellant mass fraction allows significantly more propellant within the stage. For example, the pump fed propellant mass at 6.9MPa (1000psi) has a nearly ~60% increase in available propellant and, thus, a ~60% improvement in total Impulse. The toroid tank is a more efficient use of the toroidal stage shape: 7.56m^3 (267ft^3) vs 4.644m^3 (164ft^3).

The pump fed configuration is clearly superior to the pressure fed option due to its high propellant mass fraction. Perhaps if a single spherical tank were feasible within this configuration, the pressure fed would have been more competitive. However due to the stage geometric constraints, the oblate spheroid and toroid tanks do not offer a very efficient propellant storage for a pressure fed configuration.

C. Commentary on various factors affecting propellant combinations

Given the envelope limitations, the third stage impact of a propellant combination's bulk density and efficiency (I_{sp}) is not clear. Typically, for upper stages the mission requirements and payload payoff drives the choice to the higher I_{sp} propellant type. However, because of the envelope limitations, the propellant load is severely limited. In this application, the bulk density can also be a differentiator in attaining maximum payload gains. Thus, the optimum propellant combination is not immediately obvious.

The analysis examined several propellant combinations that run the gamut from very high density to those with very low bulk densities. Each of these combinations resulted in a different propellant load due to the volume limitation. Typically, the higher the performance potential of a propellant combination, the lower is its bulk density as shown in Table 1. Additionally, each propellant combination presented various pros and cons beyond the bulk density and I_{sp}. Variables such as cryogenics, storability, insulation, etc. can play a factor in selecting the optimum propellant for the application. However, for this study the initial performance payoff is the target figure-of-merit.

Table 1. Table 1: Stage propellant mass. *Isp value representative of 6.9MPa (1000psi) chamber pressure***.**

Propellant type	Mixture ratio	Bulk ρ	I_{sp}
		g/cm3	sec
Hydrazine	-	1.02	*243*
N_2O_4/MMH	1.95	1.2	*332*
LOX/RP	2.8	1.03	*349*
$H_2O_{2(98\%)}/RP$	7.1	1.306	*322*
LOX/CH_4	3.4	0.83	*365*
LOX/LH_2	6	0.362	*454*
LOX/LH_2	10	0.481	*386*

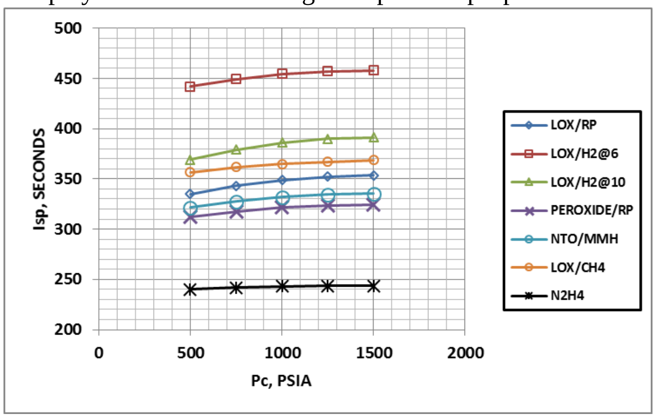

Figure 9. Isp (s) vs chamber pressure (psi) of various propellant combinations for third stage

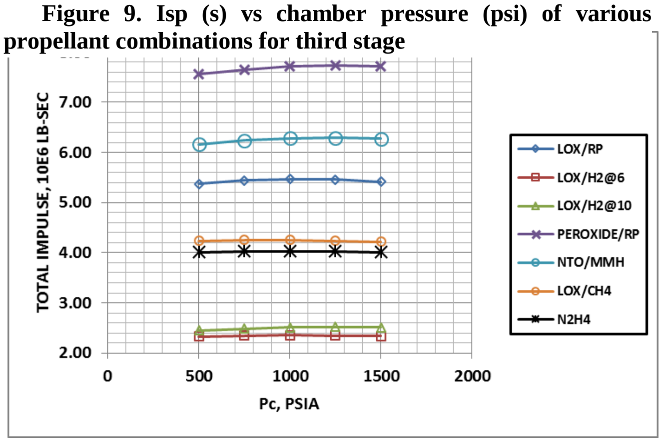

Figure 9. Total Impulse (10^6 lb*s) vs chamber pressure (psi) of various propellant combinations for third stage

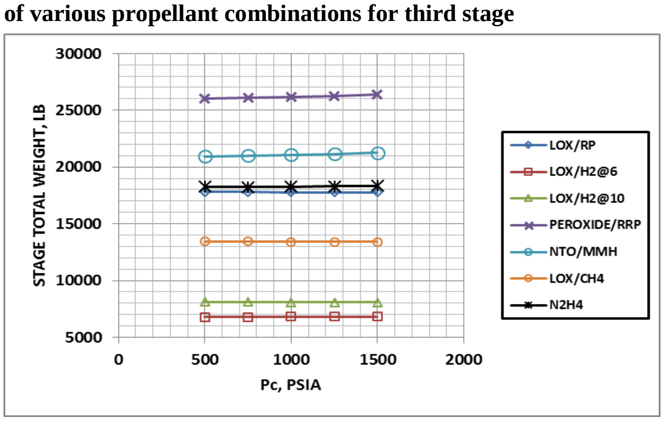

Figure 9. Stage total weight (lb) vs chamber pressure (psi) of various propellant combinations for third stage

For the bipropellant stage configurations there are additional considerations, such as mixture ratio selection, oxidizer and fuel toroid tank location (inner or outer tank), and TCA location (in between tanks or next to the payload adapter). The TCA mixture ratio was selected near the Isp peak. The stage mixture ratio shifts somewhat due to the additional GG propellant required. Therefore, when the chamber pressure increases, the required GGflow increases, thus changing the stage mixture ratio. The configuration with the TCA in between the tanks provided an increase in propellant vs. the TCA near the payload adapter. The GG is run in a fuel rich condition except for the hydrazine and peroxide (catalysis) or the N_2O_4/MMH where it operates in an ox-rich condition.

D. Comparison of various propellant combinations on third stage performance

As described in Figure 7 the chamber pressure increases the performance of each chamber. It is important to note that these relatively high Isp values are really only attainable because of the split of the engine thrust to four different chambers which allows area ratios above 150.

LOX/LH_2 at a nominal mixture ratio of 6 is clearly the highest performing propellant combination. However due to its dramatically low bulk density it is not possible to store as much propellant within the stage, thus resulting in the lowest total impulse.

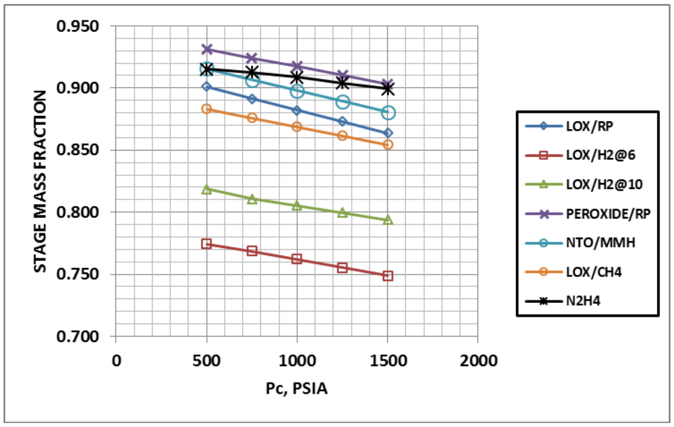

Figure 10. Stage mass fraction vs chamber pressure (psi) of various propellant combinations for third stage

H_2O_2/RP with its high bulk density and relatively high performance allows for a much larger total impulse. The remaining question is whether the overall vehicle payload performance will be driven by the high total impulse (propellant capacity) or the overall Isp performance. Figure 9 shows the total impulse attainable for each combination. The total impulse for the denser propellant combinations appears to maximize or level off at 6.9MPa (1000psi). Total impulse suggests the avenue for the highest payload performance since it describes the total energy potential within the stage. However, this may apply only to a single stage. The impact the overall stage mass and I_{sp} will need to be analyzed in the context of the overall vehicle (stages 1-3) performance.

The mass fraction results (Figure 10) follow a similar pattern and demonstrates the impact bulk density plays in the overall structure of the stage. It is interesting to note the improved mass fraction a monopropellant (with only one tank) has compared to the bipropellants. The peroxide/RP propellant combination is similar to the monopropellant due to its very high TCA MR (~7.1)

Since this third stage application is for an existing vehicle, it is unclear which characteristic will dominate the overall vehicle performance. The lower bulk density configurations allow significantly more propellant. However, this will negatively impact the lower first and second stages of the EELV. The baseline two-stage vehicle maximizes its payload performance using the two-stage configuration. If the additional weight negatively impacts the lower stages the payload capacity may not improve or diminish. An inclusive analysis, incorporating the lower stages', is thus necessary.

III. Analysis results

A. Configurations selected for analysis

From the previous figures, a chamber pressure of 6.9MPa (1000psi) was a reasonable level to maintain throughout the analysis. This follows from the observation of a leveling off or peak of the total impulse from each propellant configuration at ~6.9MPa (1000psi). This results in a propellant load and performance of each propellant combination as shown in Table 2. Each of the propellant loads represents the maximum capacity of propellant within the allocated volume for this exercise. An important observation from Table 2 is the very high total impulse available from the H_2O_2/RP propellant configuration: over three times as much compared to LOX/LH_2.

Table 2. Summary of Propellant quantities for 3rd stage assuming Pc=6.9MPa (1000psi)

	Total Mass		**Prop. Mass**		**Mass fraction**	**Structural Mass**		**Isp**	**Total Impulse**	
Propellant. type	**kg**	**lb**	**kg**	**lb**		**kg**	**lb**	**s**	**10^6 lbf*s**	**10^6 N*s**
Hydrazine	*8,283*	*18,260*	*7,526*	*16,591*	*0.909*	*757*	*1,669*	*243*	*4.032*	*17.934*
N2O4/MMH	*9,565*	*21,087*	*8,587*	*18,932*	*0.898*	*978*	*2,155*	*332*	*6.283*	*27.947*
LOX/RP	*8,061*	*17,772*	*7,112*	*15,678*	*0.882*	*950*	*2,094*	*349*	*5.470*	*24.331*
H2O2/RP	*11,878*	*26,187*	*10,895*	*24,019*	*0.917*	*984*	*2,168*	*322*	*7.722*	*34.347*
LOX/CH4	*6,086*	*13,418*	*5,287*	*11,656*	*0.869*	*799*	*1,762*	*365*	*4.255*	*18.926*
LOX/LH2 (MR=6)	*3,084*	*6,798*	*2,350*	*5,181*	*0.762*	*734*	*1,617*	*454*	*2.354*	*10.471*
LOX/LH2 (MR=10)	*3,670*	*8,091*	*2,955*	*6,516*	*0.805*	*715*	*1,575*	*386*	*2.514*	*11.182*
Star 48	*2,165*	*4,772*	*2,035*	*4,486*	*0.940*	*130*	*286*	*286*	*1.300*	*5.782*

B. Typical performance results

Analysis results describe a differentiator of performance as payload gain percentage over a standard configuration EELV (Atlas V), in this case at various orbit ΔV values, i.e. percentage gain over standard payload.

LEO ΔV is 9.3 km/s ($30.5*10^3$ ft/s) with GTO set at 11.8km/s ($38.7*10^3$ ft/s). The computation starts from the available information for the Atlas V within the public sources. Using a simple Tsiolkovsky rocket equation based computer script, a baseline simulation (standard 2 stage), and one with the third stage provide the necessary results. The initial baseline simulation serves as a comparison to published vehicle performance data. The quantitative comparison with published ULA data does not match perfectly, this occurs since such a simple computation does not take into account gravity losses, multiple burns, non-gravity turn trajectory, and atmospheric losses. However, as a simple baseline for a comparison between a two and three stage system to identify trends it should suffice. Figure 11 demonstrates ΔV vs. payload mass computation result obtained in the performance analysis. Each computation describes a single Atlas V configuration (X number of SRBs) and propellant combination. Since computations involved all six Atlas V configurations in the 500 series, (501-551) plus an additional baseline case with no third stage, there were 48 configurations analyzed.

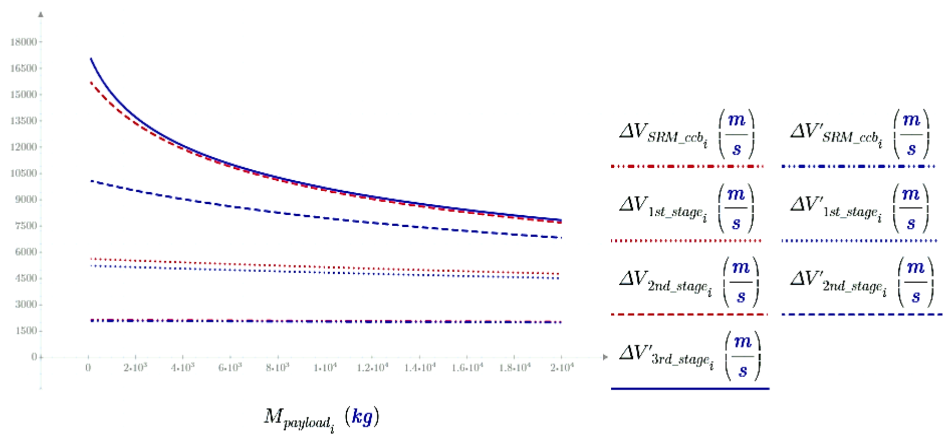

Figure 11. Sample results for performance analysis (Delta Vee vs payload) mass)

Table 3. Atlas V Payload Performance[1]

Orbit Type (ΔV to GSO)	400 Series				500 Series					
	Number of Solid Rocket Boosters									
	0	1	2	3	0	1	2	3	4	5
	Payload Systems Weight (PSW), kg (lb)									
GTO (1804 m/s)	4,750 (10,470)	5,950 (13,110)	6,890 (15,180)	7,700 (16,970)	3,775 (8,320)	5,250 (11,570)	6,475 (14,270)	7,475 (16,470)	8,290 (18,270)	8,900 (19,620)
GTO (1500 m/s)	3,460 (7,620)	4,450 (9,810)	5,210 (11,480)	5,860 (12,910)	2,690 (5,930)	3,900 (8,590)	4,880 (10,750)	5,690 (12,540)	6,280 (13,840)	6,860 (15,120)
GSO	--	--	--	--	--	--	2,632 (5,802)	3,192 (7,037)	3,630 (8,003)	3,904 (8,608)
LEO I =28.5 deg	9,797* (21,598)	12,150* (26,787)	14,067* (31,012)	15,718* (34,653)	8,123 (17,908)	10,986 (24,221)	13,490 (29,741)	15,575 (34,337)	17,443 (38,456)	18,814 (41,478)

The computation results are compared by using percentage gains over the standard payload described in the Atlas Payload users guide[1].

C. Atlas V 3rd stage performance comparisons with standard configuration for LEO

For LEO, the greatest improvement by percentage is attained by the use of LOX/LH_2 @ MR=6 with a percentage improvement of 8.5%. This is the least dense propellant configuration and the one with the highest I_{sp}. The relationship is not strictly due to I_{sp} however, since a methane configuration attains near the same percentage gain. The top three payload percentage increases are LOX/LH_2, LOX/CH_4, and LOX/RP respectively as shown in

Table 4. Payload percentage gain over baseline for GTO (11.8km/s)

Propellant. type	Bulk ρ	Isp	Prop. Mass kg (lb)	501	511	521	531	541	551
Hydrazine	1.02	243	7526 (16591)	*-33.5%*	*-32.4%*	*-31.0%*	*-29.1%*	*-27.5%*	*-26.9%*
N2O4/MMH	1.20	332	8597 (18935)	*8.1%*	*6.2%*	*4.8%*	*4.0%*	*3.4%*	*2.8%*
LOX/RP	1.03	349	7112 (15678)	*14.3%*	*11.6%*	*9.6%*	*8.7%*	*7.7%*	*7.1%*
H2O2/RP	1.31	322	10895 (24019)	*5.7%*	*4.6%*	*3.7%*	*3.3%*	*2.8%*	*2.6%*
LOX/CH4	0.83	365	5287(11656)	*19.6%*	*17.0%*	*14.8%*	*12.7%*	*11.3%*	*9.9%*
LOX/LH2 (MR=6)	0.36	454	2350 (5181)	*24.4%*	*20.8%*	*17.7%*	*16.7%*	*14.4%*	*12.8%*
LOX/LH2 (MR=10)	0.48	386	2955 (6516)	*15.8%*	*12.5%*	*10.7%*	*9.0%*	*7.7%*	*7.1%*
Star 48	-	286	2035 (4486)	*9.1%*	*6.2%*	*4.1%*	*3.0%*	*2.1%*	*1.7%*

Table 5. It is interesting to note the Star 48 motor with the highest mass fraction does not greatly affect the delivered payload. The additional total impulse offered by the additional stage is offset by the losses incurred in the previous stages of having to carry the additional weight. This is present at the lower ΔV mission, but as will be seen in the following sections, the higher ΔV missions will change this relationship.

For both the LEO and GTO analysis, the greatest percentage increase occurs in the smaller GLOW configurations (501 vs 551), mainly due to the smaller baseline payload of the smaller configuration. The larger GLOW configuration nonetheless results in a greater absolute payload increase. For example, a LOX/LH_2 (MR=10) LEO configuration has a payload gain is 688kg for 501 and 896kg for 551.

D. Atlas V 3rd stage performance comparisons with standard configuration for GTO

The GTO case follows the overall LEO trend, with the magnitude of the percentage improvements increased. An absolute value of payload mass gained is not presented to highlight that at this early conceptual stage, overall assumptions on payload mass is inconclusive until a full trajectory analysis is performed due to the effects of gravity losses. Using only percentages restricts the interpretation of the results to a comparison between the multiple stage configurations and the baseline EELV configuration. Using the data one selects a few configurations for further detailed trajectory modeling, and thus more detailed payload mass payoff. However the off-nominal mixture ratio configuration - LOX/LH2 (MR=10) becomes competitive with the LOX/RP configuration, likely demonstrating the reduction of the role total impulse has and an increase on the impact of I_{sp}.

Table 5. Payload percentage gain over baseline for LEO (9.3km/s)

Propellant. type	Bulk ρ	Isp	Prop. Mass kg (lb)	501	511	521	531	541	551
Hydrazine	1.02	243	7526 (16591)	-17.9%	-17.2%	-15.6%	-14.1%	-13.3%	-13.4%
N2O4/MMH	1.20	332	8597 (18935)	4.6%	3.6%	3.3%	3.8%	3.4%	2.7%
LOX/RP	1.03	349	7112 (15678)	6.7%	5.1%	4.8%	5.1%	4.9%	4.3%
H2O2/RP	1.31	322	10895 (24019)	4.4%	3.6%	3.6%	3.9%	3.9%	3.1%
LOX/CH4	0.83	365	5287(11656)	7.8%	6.1%	5.9%	5.6%	5.6%	4.5%
LOX/LH2 (MR=6)	0.36	454	2350 (5181)	8.5%	6.7%	6.2%	6.3%	5.3%	4.8%
LOX/LH2 (MR=10)	0.48	386	2955 (6516)	4.9%	3.2%	2.8%	3.2%	2.6%	2.0%
Star 48	-	286	2035 (4486)	0.7%	-0.2%	-0.1%	0.3%	0.0%	-0.7%

E. Atlas V 3rd stage performance comparisons with standard configuration for small interplanetary probes

Special cases where the payload is very small compared to the vehicle weight can pose interesting divergences from LEO and GTO results. These cases are typical of deep space (extremely high ΔV) missions. One example is the New Horizon's mission to Pluto launched by an Atlas V 551 vehicle. This probe had a mass of nearly 500kg and used a Star 48 motor as a final kick stage. An additional analysis based on a small payload to vehicle mass fraction shows the impact of stage mass fraction in these extreme cases. The Star 48 motor with its advantageous mass fraction performs very well against a higher total impulse and I_{sp} stage. This hints at a relationship where if the payload mass is reduced to an extreme the role of mass fraction increases.

Table 6. Delta Vee increase for Atlas V 551 (500kg payload)

Propellant. type	Mass fraction	payload vel (m/s)	payload vel (ft/s)	% improv.
Baseline	-	15,140	49,672	0%
Hydrazine	0.909	14,517	47,628	-4%
N2O4/MMH	0.898	15,706	51,529	4%
LOX/RP	0.882	16,011	52,530	6%
H2O2/RP	0.917	15,647	51,335	3%
LOX/CH4	0.869	16,433	53,914	9%
LOX/LH2 (MR=6)	0.762	16,893	55,423	12%
LOX/LH2 (MR=10)	0.805	16,481	54,072	9%
Star 48	0.940	16,854	55,295	11%

IV. Summary & Conclusion

A third stage implemented within the EELV architecture must have minimal impact to the existing configuration. The insertion of an annular stage within the payload adapter envelope allows for that low impact. However, the volume and geometry allocated to this stage is significantly constrained. As such, the balance between propellant bulk density, performance, and mass fraction needs to be quantified. The computations described in this paper show a LOX/LH_2 at a nominal mixture ratio provides the highest performance even though the bulk density is very low. However, a compromise solution with a softer cryogenic (LCH_4) and higher bulk density can provide a sufficiently attractive solution within a reasonable margin of error.

The shift of the various parameters' (bulk density, I_{sp}, mass fraction) impact upon the payload delivered to a specific ΔV depending upon the targeted ΔV is complex and requires the inclusion of all the stages for high accuracy results. A continuation of this calculation will explore the impact of additional propellant volume beyond that restrained by the confined volume. This additional volume can be attained by the use of a ESPA (EELV Secondary Payload Adapter) ring, and because the geometry configuration is similar, the concept is very adaptable to this integration. Further analysis will attempt to quantify those parameter relationships into a non-dimensional relationship to better extrapolate those relationships. Future analysis will also incorporate trajectory performance using POST software to better model the additional stage's performance given the additional variables (such as gravity losses, use of parking orbits, and multiple burns).

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